Fermi National Accelerator Laboratory

FERMILAB-Conf-82/36-THY
May 1982

FUTURE ACCELERATORS AND THEIR CONTRIBUTIONS

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I. Introduction

In the last decade we have seen tremendous progress in understanding the structure of matter and of the forces - especially strong and weak - acting between the most elementary constituents of matter. The present picture of the strong and weak forces is that they are "gauge"-interactions, structurally similar to gravitation and electromagnetism. If this picture turns out to be correct, we will have witnessed a most fundamental and revolutionary advance in our understanding of matter.

This progress could not have taken place without the existence of modern particle-accelerators. They have been an essential element in the progress of the 1970's. In the 1980's, we must rely on them and the even larger facilities now under construction to either establish firmly the correctness of the present optimism based on the "standard model" or to show the way toward the true alternative.

In this talk we will look forward to the future with a somewhat larger time-scale in mind, say 20-40 years. In doing so, one must be aware of the obvious dangers: to have tried to predict 1980 from the perspective of 1940 or 1960 would have been an exercise in futility. Nevertheless, theories of gravity and electromagnetism have survived for more than that time, and it may be less than foolish to consider from a theorist's viewpoint the next several decades.

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The ideas to follow were considered in the context of speculating on physics at 1000 TeV (in the center-of-mass) which, extrapolating from past performance of accelerator builders, we might expect to reach in the year 2020. Even if this be outrageous overextension, it is the case that theory is cheap, and that there is plenty of time to edit out the mistakes. It is also easier to interpolate than extrapolate.

In the next section we will discuss the physics issues in the context of energy scales up to 1000 TeV. We then discuss the nature of collision processes and their cross sections at these superhigh energies, what one might ask of accelerator designers, and what one might hope to learn from experiments.

II. PHYSICS PROJECTIONS

First of all, let us review where we are and where we're going in the forseeable (short-range) future. In Fig. 1 is shown the "periodic table" of the building blocks. We have to fill in top, establish existence of ν_τ and search for more quarks and leptons. It would also be nice to understand the origin of this peculiar pattern. Most impressive, however, is the status of the theory of the three basic forces (strong, weak, electromagnetic). We have quantum electrodynamics (QED), valid to a 10^{-16} cm distance scale. The status of the theory of the strong force, QCD, is believed by many to be as solid as QED. Just ask any theorist (don't ask experimentalists) and chances are that he or she will tell you that. The electro-weak theory is as solid as the other two theories provided (and <u>only</u> provided) the $W^{\pm}$ and the Z^0 properties come out as predicted. The precision of electro-weak predictions is competing with the precision of QED predictions--it is at the

1% or half-level already. And if something goes wrong at the 5% level, this could cause terrible panic in the theory community.

These three gauge theories, while accounting for a very diverse set of phenomena, all look similar structurally. At distances short compared to the electro-weak scale of 100 GeV, the phenomena really are supposed to become very similar, and in fact become more and more indistinguishable as the energy scale goes up. This gives the possibility of total indistinguishability at the grand unified scale of 10^{15} GeV. That would be wonderful, if true.

Thus, at short distances, these three forces are supposed to be weak forces characterized by their fine structure constants of 1/60 for U(1), 1/20 for SU(2), and 1/8 for SU(3). It's always 1 over a large number, so that a perturbation theory exists. Theorists can predict and experimentalists can measure. And, given that these theories become so well-defined, what is there left to do? The best way to find out is simply to turn off those three coupling constants, i.e. replace them by zero. If the three gauge theories are a complete description of nature, then there should be almost nothing left in the limit of zero coupling. We should just have free particles: gauge particles, quarks, and leptons sitting around doing nothing except interacting gravitationally.

But this is not what happens in the standard model. There _is_ something left; it is what is called the Higgs sector. There are extra ugly scalar bosons. They interact with each other through _ad hoc_ couplings, and interact with the quarks and the leptons through _ad hoc_ Yukawa couplings, as well as generate CP violation by some obscure mechanism. And there is no apparent connection of these interactions with gauge principles and gauge theories.

All of this leads to something like 20 ± 5 (I don't know the exact number) arbitrary parameters in the theory, parameters that are as disparate as the mass of the electron and the mass of the top quark. In the standard model, all these parameters are put in by hand. Were neutrinos to have mass, the dynamic range of the arbitrary parameters would expand to 9 or 10 orders of magnitude. This is plenty to keep us mystified for some time to come -- it is a central problem of high-energy particle theory.

But while there is plenty of room for lingering doubts on the validity of QCD and electroweak theory, it still remains true that one now has an impressively satisfactory situation. The theorists smugly sit on top of the heap looking down at experimentalists. And if an experimentalist dares to find an answer which disagrees with the theory, he risks being looked at with scorn and disbelief. Such experimentalists will have to bravely resist a considerable amount of social pressure. I encourage them all to do that (including myself).

B. Energy Landmarks

Let us now try to find some energy landmarks between present energies and 1000 TeV in the c.m.s. First of all, there is the hundred GeV energy scale. That is low energy physics where we expect to find the $W^{\pm}$ and the Z^0. It is an energy scale where as yet the electroweak gauge theory does not reach its fully symmetric, unbroken asymptotic form valid at very short distances.

What are the options for this energy scale? First of all, suppose the standard SU(2)XU(1) gauge theory is correct and the mass of the Z^0 when it's measured comes out right on the mark, within a GeV or so. Everyone will get excited about limiting the behavior of the theory at higher energies via the precise measurements of the radiative corrections. The development of the electroweak theory might be very much like that of electromagnetic theory 20 or 30 years ago.

But this may not happen. There are a variety of alternative gauge theories. Generalizations of the standard SU(2)XU(1) model exist, some invented by the practitioners of the standard theories themselves.[1] These are characterized by extra intermediate bosons. In particular, there will certainly be more Z^0 bosons, and in these generalizations it is a certainty that at least one of them is no heavier than the standard Z^0.

There are other ideas emerging from work on technicolor models.[2] One may imagine that the weak interaction, while weak at energies large compared to a hundred Gev, becomes stong somewhere around a hundred GeV in the center-of-mass, very much like quantum chromodynamics becomes strong at the one GeV mass scale. Then the $W^{\pm}$ and the Z^0 could actually be dynamical objects, composites, with complicated structures much like the ρ and ω in strong interactions. The dynamically-generated $W^{\pm}$ and Z^0 might have a different mass than the standard mass; Abbott and Farhi,[3] for example, estimate 110 GeV. This is not too far away from the standard number, but nevertheless it is different. And the phenomenology could be quite distinct relative to the standard model.

There is another arch-conservative view, for which I am partly responsible.[4] It is a phenomenology where one may not even have $W^{\pm}$ or Z^0, but where the weak interactions are mediated by some set of weak quanta of more obscure origin. One can still account for the low energy measurements of neutral currents. But even in this very minimal view, it still follows that something has to happen in the charged-current weak interactions below 170 GeV; it must deviate from the point four-fermion Fermi coupling. So in all cases it seems that by the time we exceed the hundred GeV scale (which the next generation of machines should do) the direction of the weak interaction theory should be rather well mapped out. Either it goes according to expectations or else we should have quite a good idea of what kind of alternatives nature has chosen.

As we go beyond the 100-GeV weak interaction scale, there are a few more landmarks, although they are much hazier. Between 20 and 400 GeV one anticipates finding the last of the standard quarks and leptons. If the generation structure in Fig. 1 (the three generations of building blocks) survives and is not a fraud, then the top quark should have been found by the time one gets to $E_{c.m.s.} > > 400$ GeV. And if there are other standard quarks and leptons having the same kind of pattern we now see, then there is trouble[5] with the ρ parameter which measures the ratio of the neutral current to the charged-current neutrino cross sections if the masses exceed 400 GeV.

The ρ parameter is precisely determined by data to be very near one. That's no accident; in the standard model it is one within radiative corrections, but radiative corrections involving very heavy quarks and leptons upset that ratio.

There are loopholes. There could be nonstandard fermions which are heavier, provided that they are degenerate electroweak multiplets, i.e., the mass of the up-type and the down-type fermion is precisely the same. Also electroweak singlets which don't couple to the $W^{\pm}$ and Z^0 system at all could also exist.

But in any case, we just can't go on with further replications without running into trouble. That is at least encouraging that Nature might be more creative as one goes up beyond the hundred-GeV scale.

Beyond 300 GeV or so there is room for right-handed gauge bosons, associated with a left-right symmetric gauge theory. There is no particular predicted mass, but only rough lower bounds coming from the absence of right-handed currents at low energies.[6] The typical number is something like 300 GeV for that lower bound. By the time we reach the 1 TeV scale, the Higgs sector has to show itself. There is a ceiling on the mass of the standard Higgs boson at that point.[7] If the Higgs-boson mass is $\lesssim$ 40-100 GeV, the e^+e^- colliders should find it. But if the mass is above 100 GeV, it is not clear that one <u>can</u> find it.

Now there are various options for the nature of the Higgs system. One is the orthodox model where it is an isolated single neutral spinless elementary particle. It just sits there in the theory in lonely splendor, but in a rather incomprehensible way.

On the other hand, the Higgs particle may be a composite structure--one member of a big family. This is the technicolor option, where one thinks of the Higgs boson as a bound state of some new quark and antiquark, bound through a force which is modeled after QCD but on a mass scale of 1 TeV rather than on the mass scale of 1 GeV. In that model one has a whole new world of strongly interacting techni-hadrons, some of which are thought to be light (10 to 50 GeV?). Some of those light ones could be charged and could be found in e^+e^- colliders today or tomorrow or yesterday at PEP and PETRA.

Some of the other technihadrons can be expected to be coupled to gluons. These tend to be heavy, between 300 and 1,000 GeV. You can imagine technirhos, techniomegas, technietas, etc.----all our old friends in hadron physics repeated again at a mass scale a thousand times bigger. That would be great fun experimentally for a collider at a thousand TeV---although the technihadrons are not so easy to make in strong interactions. Cross sections are at the subnanobarn level, so high luminosity would be of importance.

However, the technicolor picture by itself does not explain the quark and the lepton masses. To do that, the technicolor advocates go further and complicate the theory in a rather awkward way. But it seems to be necessary to do this. At a still higher mass scale it is proposed that there is something called extended technicolor. It is yet another gauge interaction with new intermediate bosons with a mass scale of somewhere around 100 TeV.

The quark mass is then produced by a radiative effect as shown in Fig. 2. The intermediate fermion techniquark has a dynamical mass of order 1 TeV. The quark mass is

$$M_q \sim \frac{M_Q^3}{\mu^2} \sim \frac{(1\ \mathrm{TeV})^3}{\mu^2} \qquad (1)$$

which gives the scale of the mass μ of the ETC gauge boson. Nobody has made a realistic model of all this. The basic idea is very pretty, but somehow the machinery still has some sand in it.

There is yet another energy landmark, one that seems to me to be relatively solid if the standard electroweak theory is correct. Assume there exists W^+ and Z^0 coupled according to the gauge theory ideology, but assume nothing about the Higgs system. Consider the process $t\bar{t} \to W^+W^-$ and look (Fig. 3) at the Feynman diagrams coming from single Z^0 or γ exchange and single bottom exchange. Upon adding up those amplitudes, one finds that in the J=0 partial wave the amplitude at high energy starts blowing up.

$$M \sim \frac{\alpha_W M_t E_{c.m.s.}}{M_W^2} \qquad (2)$$

The amplitude should, by unitarity, be <1 at all energies. But it has an extra power of center-of-mass energy in it.

In the standard model that term is canceled by the diagram (Fig. 4) in which the $t\bar{t}$ system annihilates through the Higgs channel. (The Higgs boson is what in the standard model gives the top quark its mass.) But if there is something more complicated going on giving the top quark its mass, that contribution has to show itself when one gets up to this energy scale. Otherwise unitarity would be violated. The limit on the energy scale is inversely proportional to the top quark mass, and, for $M_t > 30$ GeV, is < 10 to 30 TeV, well below 1,000 TeV. Of course, for the lighter quarks the limit is higher, so that the top quark gives the strictest bound. Therefore this is another indicator that we must understand better this problem of mass of the quarks and leptons well before we get to a thousand TeV in the center-of-mass.

We may entertain compositeness not only for the Higgs particles, but also for intermediate bosons, and/or quarks, and/or leptons. Could they be composite? Here experiment already gives a guide. Again, in e^+e^- colliders the agreement of PEP and PETRA measurements with the point-like behavior of collision cross sections puts a lower limit of about 100 GeV on any energy scale for internal structure. So above that, one can entertain[8] the notion of compositeness of leptons and quarks. Probably the theoretically-favored energy scale would be the same energy scale in which fermion mass generation is to be understood. There are very nice theoretical attempts to do this. At present, it's a respectable endeavor and in some ways, a very attractive one.

We summarize all these landmarks in Fig. 5. One sees down at low energies (< 100 GeV) relatively solid landmarks, with precise expectations of what one should find. This is mainly the business of either really establishing the present picture of weak interactions experimentally, making it absolutely solid, or of destroying it and replacing it by something else.

At higher energies the landmarks become imprecise. Nevertheless, one does see a distribution of landmarks which tend to populate the region below 1000 TeV. And one can imagine that 30 years from now when the proposals are written for the 1,000 TeV machine, there will be plenty of scientific justification for building it.

IV. PROCESSES AND CROSS SECTIONS

A. Soft processes

The most accessible physics involve study of soft processes, such as measuring total and elastic cross sections, inclusive spectra, multiplicities, and correlation functions. While this is a relatively quiet subject nowadays, the situation might change in the future. One has to keep in mind that in the year 2020 perturbative QCD is likely to be relegated to the engineering department, not worthy of being taught anymore in physics courses. People will be bored with it. It will be nonperturbative QCD that is left. Even there, the easy problems like calculating the mass of the ρ, or nucleon, or Δ will have been solved. The real problem remaining will be to connect Reggeons and especially the Pomeron with QCD. The rise in the total cross section may be very large. Multiplicities will be very high. Do they follow a QCD pattern? There will be many subprocesses per event and probably of order one charm pair per collision just because there are so many particles produced.

But then there might be very new phenomena. Of course one can invoke cosmic rays and Centauros and the like. But a somewhat more specific possibility would be the ultimate breakup of the proton into free physical quarks, if in fact such things do exist. A little bit of dirt in QCD might allow that to happen somehow.[9]

There might also be collective or coherent phenomena (I don't know quite what that means) that go on because the local fields and the energy densities in the region of the collision will be very high. The energy in gluon fields in particular is very large; half the kinetic energy is in gluons. Furthermore, in QCD all the gluons, no matter what their rapidities, interact with all the other ones. There's no strict short-range correlation in rapidity. All the longitudinal phase space of the partons in the projectiles can get heated up at the instant of collision. And it may be that the higher the energy, the hotter they get. Maybe there is some critical temperature beyond which new phenomena happen (Quark-gluon plasma formation? Shock waves or other hydrodynamic phenomena? Production of metastable vacuum?) This is the kind of thing that relativistic heavy ion people talk about with some seriousness nowadays.[10] It is all very vague, but maybe after 30 more years of QCD it won't be so vague.

One should keep in mind that these soft physics considerations also apply to e^+e and ep machines as well. The photon-photon collisions at such high energies are interesting in their own right. The $\gamma\gamma$ cross-sections would be $< 10^{-30}$ cm^2. In ep colliders the photon-proton cross-section exceeds 10^{-28} cm^2. Thus modest luminosities again can give rise to a lot of soft collisions, even for ee and ep colliders.

B. Hard collisions

Hard collisions are processes such as production of very heavy quarks, dileptons, or high $p_\perp$ jets in pp collisions. In e^+e^- collisions, it is any annihilation mechanism via an intermediate boson such as γ or Z. Hard-collision cross-sections typically fall as $E^{-2}_{c.m.s.}$. In the case of new flavor production, one might be a little more optimistic. But I think the greatest optimists would still have a (mass)$^{-2}$ dependence of the production cross sections, but perhaps with a normalization on the large side. Some of these cross sections are sketched in Fig. 6. Non-resonant e^+e^- annihilation sinks out of sight by the time one gets into this 10^3 TeV energy scale, even if one could ever reach it.

The greatest hope for being able to see something via e^+e^-machines of nominal luminosity would probably be resonant production of a heavy $Z^{0'}$. The requirement $\sigma_{res} \gtrsim 10^{-36}$ cm^2 implies $M_z \lesssim 50$ TeV. That really is not too bad. But there's no guarantee that a heavier $Z^{0'}$ exists. Probably the prudent strategy is to first hunt it down in $p\bar{p}$ colliders before chasing after it in e^+e^-.

In the case of hard collisions of hadrons, collision cross sections again tend to fall like $E^{-2}_{c.m.s.}$. We show in Fig. 6, in terms of the constituents' sub-energy, some crude estimates of these cross-sections; one wouldn't want to consider sub-energies much more than a few hundred TeV. There the typical cross sections are $10^{-36 \pm 1}$ cm^2. But I think if one manages to produce a heavy-quark pair or some other hard process, the signal-to-noise problem might not be all that bad. All the hard collision processes are falling with energy in the same way, and it's not so often that one would see, say, 50 TeV coming out at 90 degrees relative to the collision axis. That can be picked out from a great deal of background.

C. Breakup

What if some of our "elementary" constituents are composites? Then there may be a little more room for optimism as far as cross sections are concerned, but not too much. If Higgs bosons are composite, then so are the intermediate bosons, at least in part. In the gauge theory, the longitudinal polarization state of an intermediate boson is, loosely speaking, a Higgs particle. So given that the Higgs bosons are composite and interact strongly with each other, it follows that at least some piece of the intermediate bosons will interact strongly with each other as well. This is what happens in the technicolor models, where the technihadrons will decay strongly into intermediate bosons. The situation is analogous to resonant production of the rho in e^+e^- collisions through an intermediate photon. The analogue here is production of a technirho or techniomega in quark-antiquark annihilation via a gluon (which couples into the technicolor world). Having made this techniparticle resonantly, it then decays strongly into some collection of intermediate bosons or Higgs particles. The cross sections are typically[11] $10^{-35 \pm 2}$ cm^2.

On the other hand, all of the W may be a composite structure for reasons that go beyond the standard gauge theories.[12] If so, they may break up at high energies into their constituents. Similarly, if quarks or leptons are composite, then once one gets to the scale of compositeness, an optimist would expect that, at sufficiently high energies, whenever the impact parameter is small compered to the size of the composite system, there is a good chance of breaking up the projectiles into constituents. So the breakup cross section would be on the order of the square of the size of the particle at high energies, multiplied by the square of the number of constituents per projectile.[13]

In summary, one sees that the nominal order of magnitude for most processes other than the soft processes are, at this energy scale of 100 to 1,000 TeV, of order $10^{-35 \pm 3}$ cm^2. High luminosity is important.

IV. SUMMARY

First of all, it should be clear that it may well be madness to project present theory so far into the future. A second caveat is that we assumed that the criterion for the future is attainment of the highest center-of-mass energy. I do think the name of the game is energy, and high center-of-mass energy is what we really ought to shoot for as the first priority. Nevertheless, that's not the only criterion. Omitted criteria are the relative cleanliness of e^+e^- colliders, as well as the many virtues of fixed target studies at lower energies.

Also, ep colliders have hardly been mentioned. The ep physics in some way interpolates between the two extremes of e^+e^- and $p\bar{p}$. However, the main inference to make is that it seems that in the future large colliders are a necessity. The typical cross section estimates follow from common-sense dimensional analysis, using a mass scale of somewhere between 10 and 100 TeV. For a 1,000-TeV machine the cross sections naturally come out somewhere in the $10^{-35 \pm 3}$ cm^2 range. Of course there are possible exceptions to this inference that the "interesting" cross sections are low. There is the intrinsic interest of looking at the total cross section and the gross processes because they're there and may show their own special features. Also, one can think about proton breakup into free constituents such as physical quarks. And "collective" effects associated with the very high energy density in the collision might occur.

But on balance, it does seem that high luminosity as well as high energy is very desirable. Just from the point of view of beam power, that seems to provide an enormous challenge. But it may be that in the year 2020 power is very cheap and this is a non-issue. I think we should also not rule out in advance the possibility of an enormous conventional machine being built at this energy scale by somehow or another pushing down the unit cost. However unlikely it may seem that such a thing would be built, it might be interesting and fun to learn whether such a machine is even feasible and what it would look like.

In any case, the present progress and future promise signals the very fundamental nature and scientific importance of physics of the great accelerators of the future. There is every reason to expect that they will contribute as much to our understanding as their predecessors.

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FIGURE CAPTIONS

Fig. 1: "Periodic Table" of quark and lepton building blocks.

Fig. 2: Origin of quark mass a la technicolor.

Fig. 3: Production of W pairs by $t\bar{t}$ annihilation.

Fig. 4: Production of W-pairs by $t\bar{t}$ annihilation via an intermediate Higgs boson.

Fig. 5: Energy landmarks.

Fig. 6: Some (rough) cross-section estimates.

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† Talk given at the Pan American Symposium on High Energy Physics and Technology, January 4-8, 1982, Cocoyoc, Mexico .

Quarks		Leptons	
u	d	e	ν_e
c	s	μ	ν_μ
	b	τ	(ν_τ)

Fig. 1

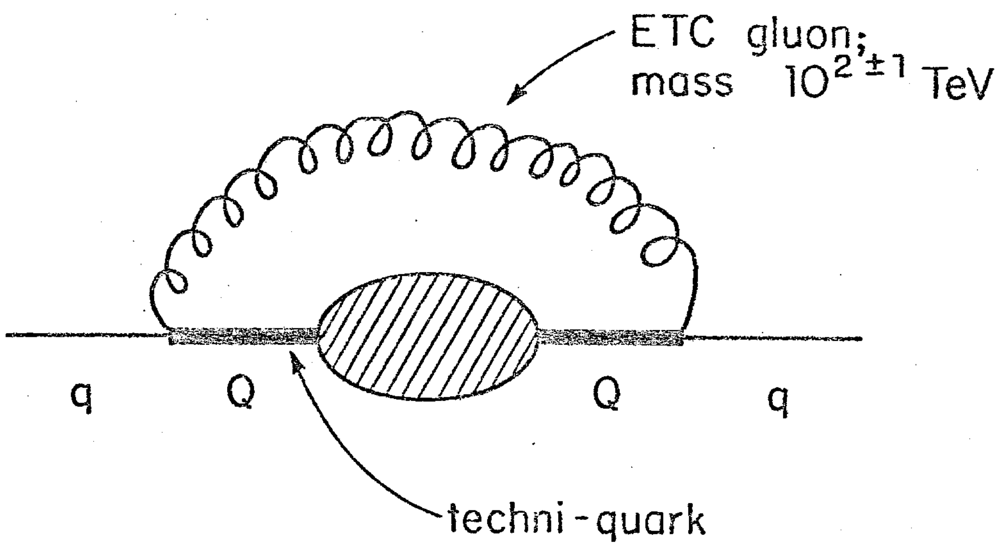


Fig. 2

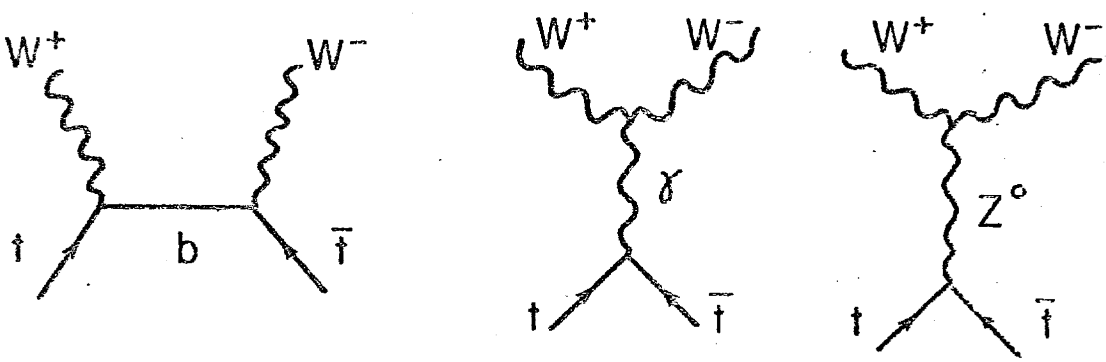


Fig. 3

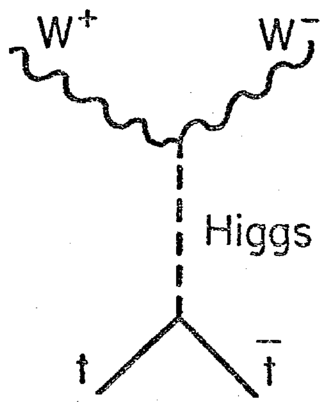
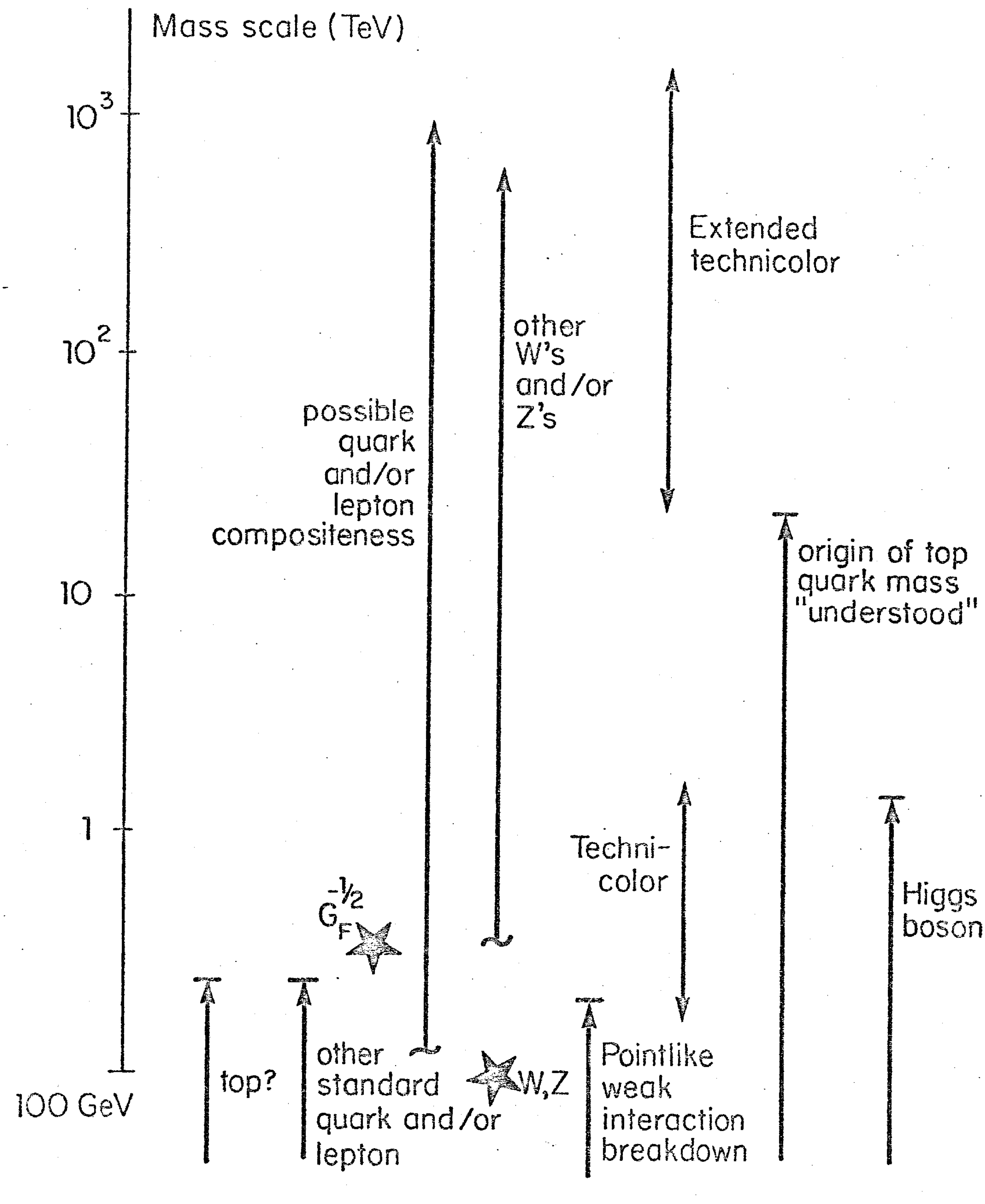


Fig. 4


Mass scale (TeV)
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10^2
10
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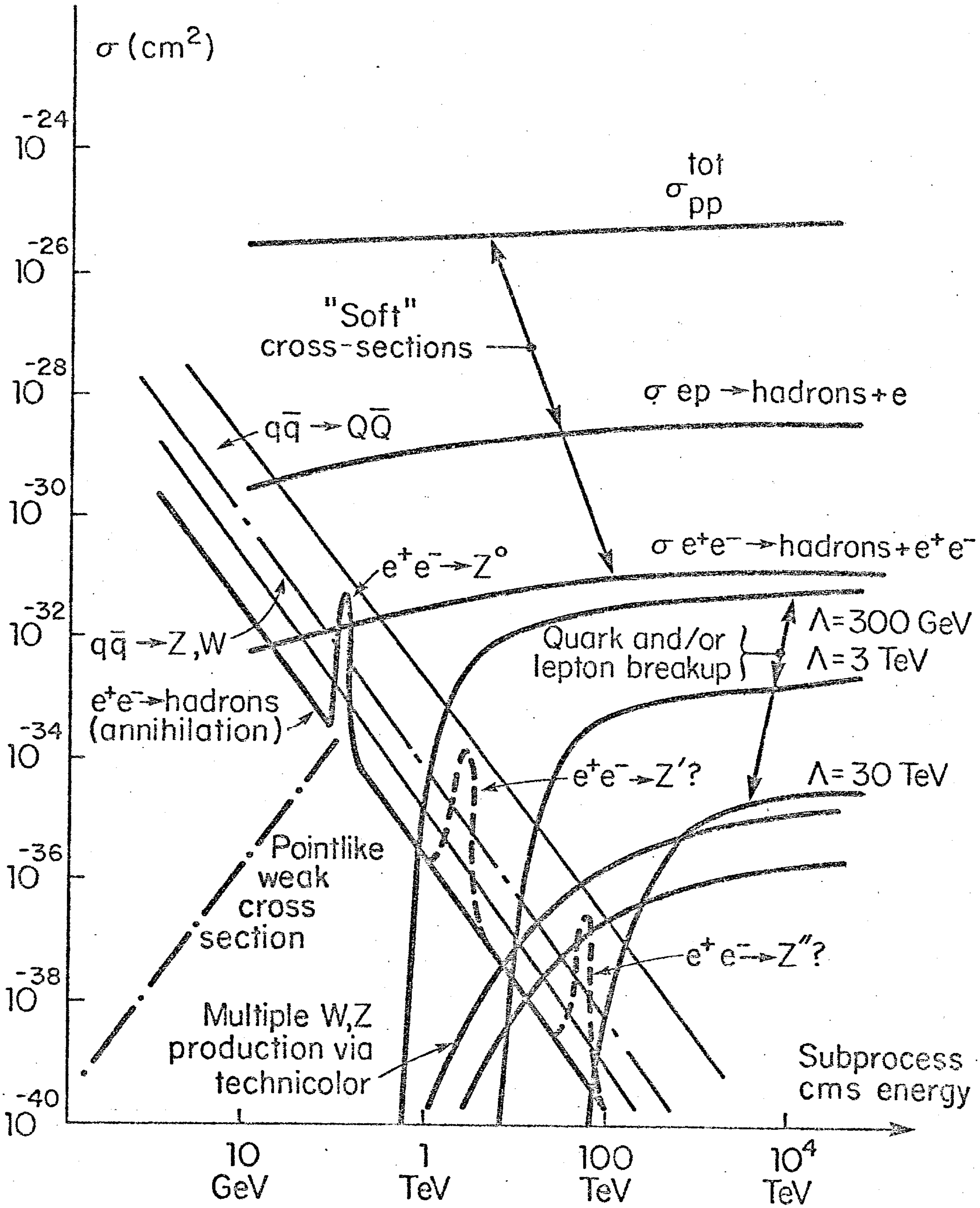
100 GeV
possible
quark
and/or
lepton
compositeness
other
W's
and/or
Z's
Extended
technicolor
origin of top
quark mass
"understood"
Techni-
color
Higgs
boson
$G_F^{-1/2}$
top?
other
standard
quark and/or
lepton
W,Z
Pointlike
weak
interaction
breakdown

Fig. 5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10⁻²⁶
10⁻²⁸
10⁻³⁰
10⁻³²
10⁻³⁴
10⁻³⁶
10⁻³⁸
10⁻⁴⁰
σ tot pp
"Soft" cross-sections
σ ep → hadrons + e
q q̄ → Q Q̄
σ e⁺e⁻ → hadrons + e⁺ e⁻
e⁺ e⁻ → Z°
q q̄ → Z, W
Λ = 300 GeV
Quark and/or lepton breakup
Λ = 3 TeV
e⁺e⁻ → hadrons (annihilation)
e⁺e⁻ → Z′?
Λ = 30 TeV
Pointlike weak cross section
e⁺ e⁻ → Z″?
Multiple W,Z production via technicolor
Subprocess cms energy
10 GeV
1 TeV
100 TeV
10⁴ TeV

Fig. 6